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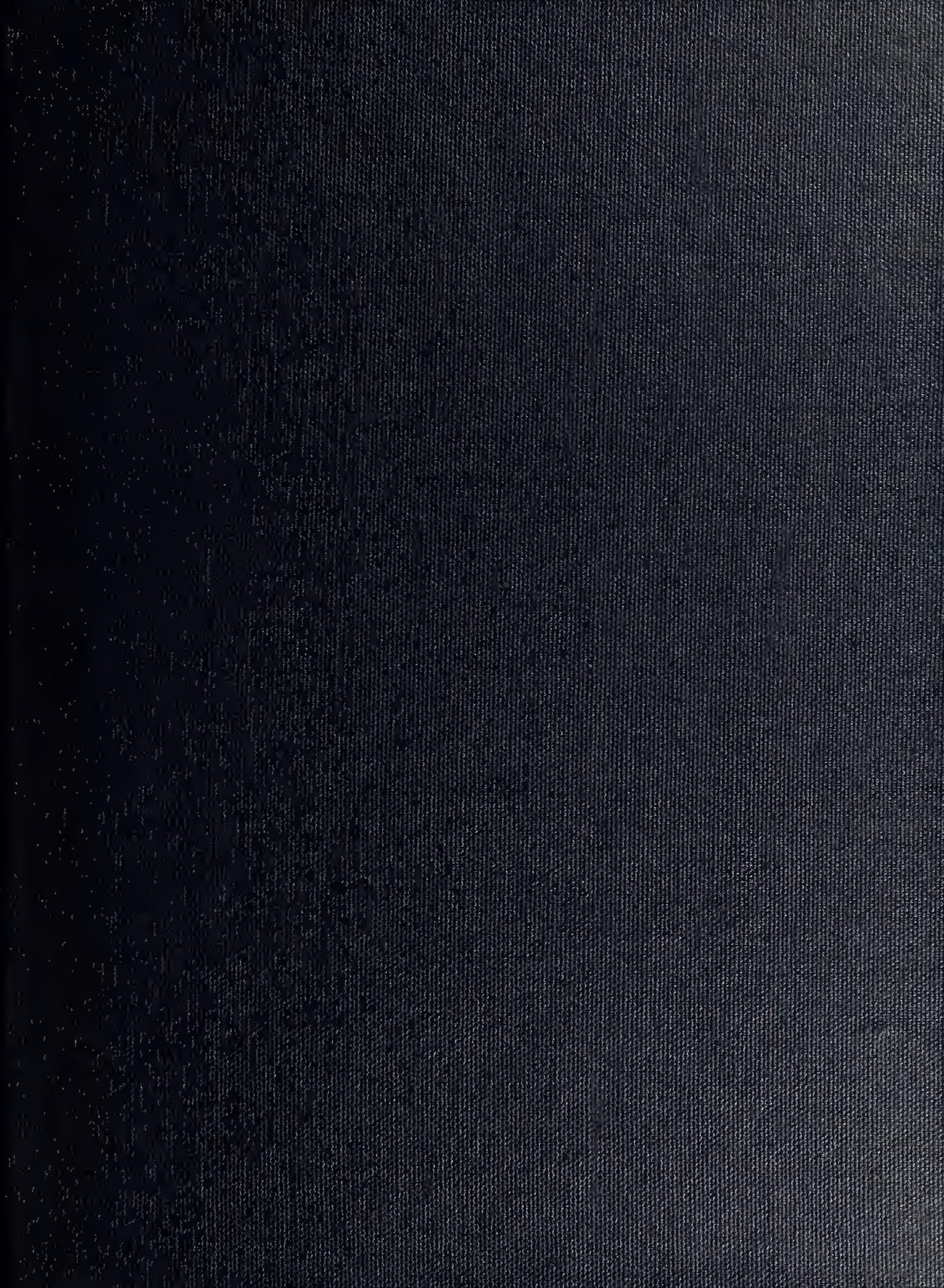


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NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

HOLOGRAPHIC INVESTIGATION OF METALLIZED
SOLID PROPELLANT COMBUSTION IN A
THREE-DIMENSIONAL MOTOR

by

James Blake Rubin

September 1986

Thesis Advisor:

David W. Netzer

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Holographic Investigation of Metallized Solid
Propellant Combustion in a Three-Dimensional Motor

by

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Lieutenant, United States Navy
B.S., Purdue University, 1979

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

An experimental investigation was performed to determine the feasibility of obtaining particle size data using pulsed-ruby holography in a three-dimensional metallized solid propellant rocket motor. Holograms of a USAF Resolution Target and a LEOS dot target were taken under various conditions, with the system resolution determined to be under 5 microns. Good quality holograms were obtained at pressures of 91, 110, and 280 psi using an HTPB/ammonium perchlorate propellant with 2 percent, 20 micron aluminum. Holograms were not successful at a pressure of 240 psi and 560 psi with a 2 percent aluminized AP/GAP propellant. For this propellant, transmittance tests indicated complete opacity during the steady-state portion of the burn.

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I. INTRODUCTION

Aluminum is added to solid propellants to increase performance and to suppress high frequency combustion instabilities. The aluminum provides a higher specific impulse, but incomplete combustion of the aluminum agglomerates and two-phase nozzle flow losses reduce the combustion efficiency. The overall combustion efficiency of the motor is highly dependent upon the particle sizes within the combustion chamber. During the propellant burning process, the metallic particles are exposed to the surface of the propellant. Some of the particles leave the surface rapidly while others first combine and form agglomerates on the surface. The smaller particles generally undergo complete combustion, while the larger particles may not burn completely and/or can result in large condensed oxide particulates and are subject to aerodynamic loads caused by the large acceleration gradient between the gas and liquid phases. This interaction of gas and particle flow is extremely important in the analytical modeling of the solid propellant motor exhaust nozzle expansion process. The flow dynamics are very sensitive to the size and distribution of the particles, and very little data is currently available.

Knowledge of the behavior of particulates in the combustion chambers and exhaust nozzles of solid propellant motors is of great interest due to the effect on performance and specific

impulse. All current models are semi-empirical and are generally based upon particle size distributions which were obtained from motion pictures and/or collected particules from strand burners or collected nozzle exhaust flows from small motors [Ref. 1]. The highly difficult task of generating the particle size distribution data in the combustion chamber, from the propellant surface to the nozzle entrance seems ideally suited to holography.

Holography is under investigation at the Naval Postgraduate School as a technique to obtain quantitative data on the effects of propellant properties, operating pressure, and nozzle geometry on the behavior of metallized particulates within the grain port and nozzle of solid propellant rocket motors. These data are needed to improve performance predictive capability, provide input to current combustion models, provide data on the effects of motor and propellant conditions on the exhaust plume, and to provide particle data to increase the accuracy in stability and specific impulse analyses. [Ref. 2]

The holographic technique provides a large field of view and both amplitude and phase information, which allows a 3-D image to be reconstructed. Narrow pass laser line filters are incorporated in order to eliminate the flame envelopes surrounding the burning particles. Smoke generation presents a problem because the laser light can only penetrate a finite amount. Another problem caused by the smoke is due to unsteadiness, which makes it difficult to maintain the optimum

reference beam to scene beam illumination ratio, between 5 and 10 to 1. In order to overcome the problems and to obtain a hologram of the steady-state combustion process a very precise method of firing the laser must be incorporated into the system in use.

The laser holographic system used in the present investigation consisted of a pulsed ruby laser [Ref. 3] together with a holocamera [Ref. 4]. The operating wavelength was 694.3 nm with a beam diameter of approximately 3.2 cm. A one joule pulse with a 50 nsec pulselwidth has been used.

Past efforts at the Naval Postgraduate School have included the use of strand burners within a nitrogen purged combustion bomb and small 2-D, windowed motors. Propellant strands were burned at pressures of 34 and 68 atm, with aluminum concentrations of up to 15%. Successful elimination of schlieren effects and flame envelopes was achieved in the holograms using diffuse illumination. Holograms in the 2-D motor were successful for propellants with up to 5% metal additive and pressures to 59 atm, as well as at 33 atm and 10% aluminum. Higher concentrations of aluminum, 10% and 15%, and increased pressures made the taking of holograms impossible [Ref. 2]. Present efforts are directed at a 3-D, windowed rocket motor.

Diffuse illumination has been used in the past to minimize the presence of schlieren produced by temperature and density variations of the combustion gas during the burn. The diffuse illumination produces speckle in the reproduced image, which

was reduced through the use of a spinning mular disk at the focal point of the observation microscope.

In the 3-D motor investigation conducted by Yoon [Ref. 5], methods for determining the reference to scene beam illumination ratio were established. In addition, all the current test stand apparatus was installed and set in working order. Yoon's investigation also established a requirement for a more accurate method of firing the laser-holocamera apparatus.

The objects of this investigation were:

- (1) to develop a computer controlled firing solution for triggering the holocamera,
- (2) to develop a reliable method for obtaining the holograms,
- (3) to obtain good quality holograms from different propellants and/or rocket motor geometries.

II. DESCRIPTION OF APPARATUS

A. BACKGROUND

Three main systems were used to complete the current investigation. A pulsed ruby laser system and holographic camera, a 3-D windowed rocket motor, and a krypton-ion reconstruction laser with a microscope and camera.

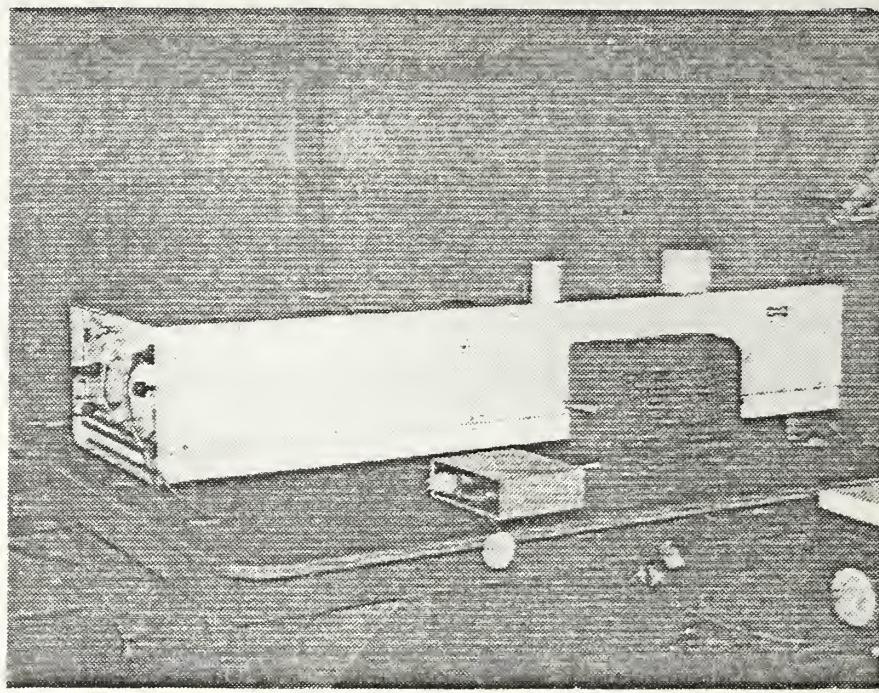
B. EQUIPMENT

1. Laser and Holocamera

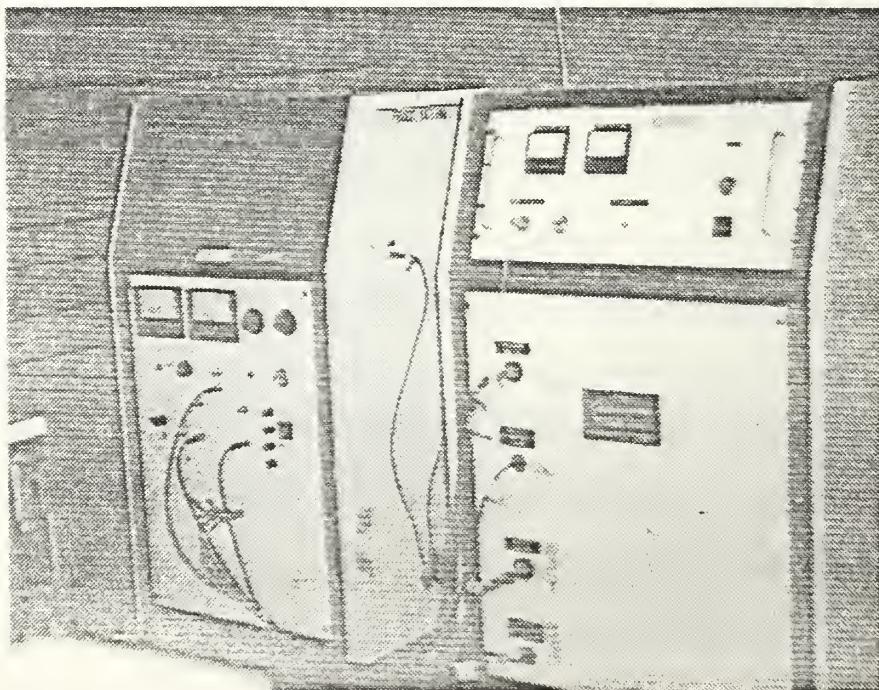
The pulsed ruby laser operates at a wavelength of .694.3 nm with an output beam diameter of 3.2 cm. The system emits a single Q-switched pulse of approximately 1 joule total energy and approximately 50 nsec duration. The laser system is described in detail in Ref. 3 and is shown in Figure 2.1.

The holocamera [Ref. 4] was used with AGFA-GEVAERT 8E75 HD photographic plates to record the image of the 3-D motor combustion process. The lens-assisted holographic technique was incorporated into the holocamera to increase the resolution. An electrical Uniblitz shutter is used to protect the photographic plates. The holocamera and motor are shown in Figure 2.2.

In an effort to improve the photographic recordings, the plano convex lenses in the holocamera were replaced and a complete, end-to-end, system alignment was conducted. Some investigation was made into the reduction of "fringes" which

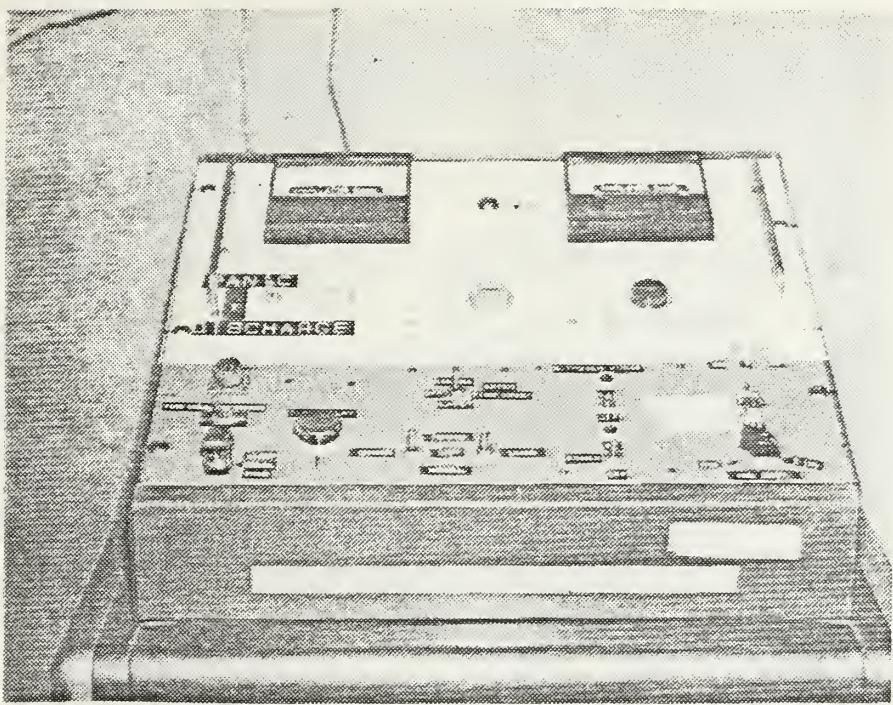


a. Pulsed Ruby Laser



b. Pulsed Ruby Power and Capacitor Banks

Figure 2.1. Pulsed Ruby Recording Laser and Control Panel



c. Pulsed Ruby Laser Control Panel

Figure 2.1. (continued) Pulsed Ruby Recording Laser and Control Panel

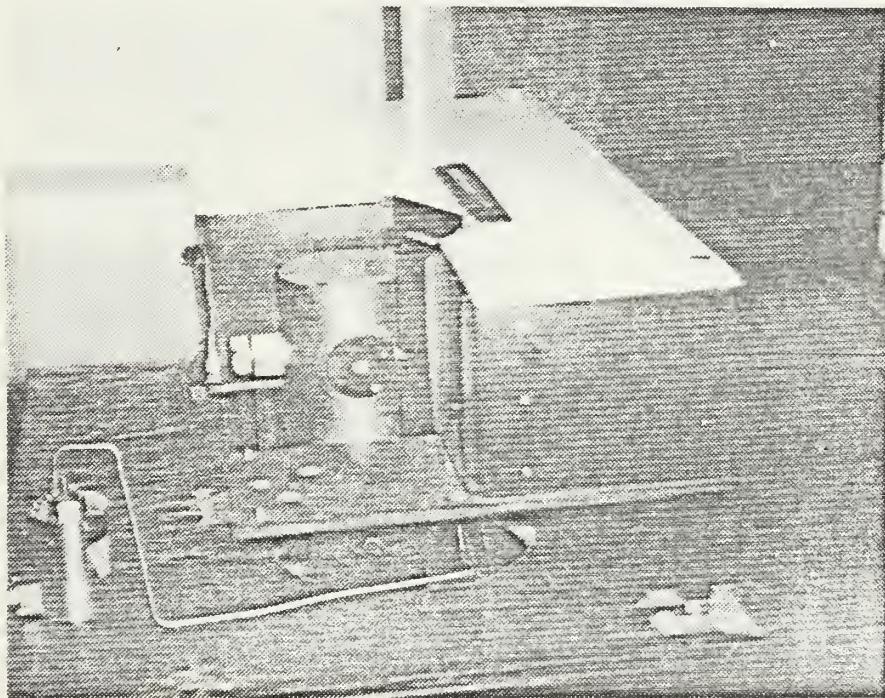


Figure 2.2. Holocamera and Vertically Mounted 3-D Motor

are introduced into the hologram due to the nonperpendicular alignment of the L3 and L4 lenses and narrow pass filters in the removable holocamera box.

The recommendation, made by Yoon [Ref. 5], to operate the laser/holocamera system by an automated means was implemented. An electrical connection was made from the system control panel to a data bus on an HP-9836S computer system. A program, which samples the chamber pressure data of the 3-D motor, fires the laser when the desired trigger pressure and time delay are met. This method allows the hologram to be taken at or near the peak pressure, prior to the production of large quantities of smoke during tailoff.

2. Hologram Reconstruction

A Spectra-Physics krypton-ion CW gas laser was used to rear illuminate the developed hologram. The plate was mounted in the holocamera box and then mounted on a stand at a 60 degree angle to the laser beam. The laser had an output of 0.5 watts at a wavelength of 647.1 nm. A rotating mylar disk was used at the focal point of a variable power microscope. This reduced the amount of speckle present in the reconstructed hologram. Photographs were taken via a camera mount on the microscope. Figure 2.3 shows the system as used.

The krypton-ion laser, as shown in Figure 2.4, was also used to determine the best obtainable resolution of the system. The increased coherence and use of the same laser for taking and reconstructing the hologram should provide the best possible resolution.

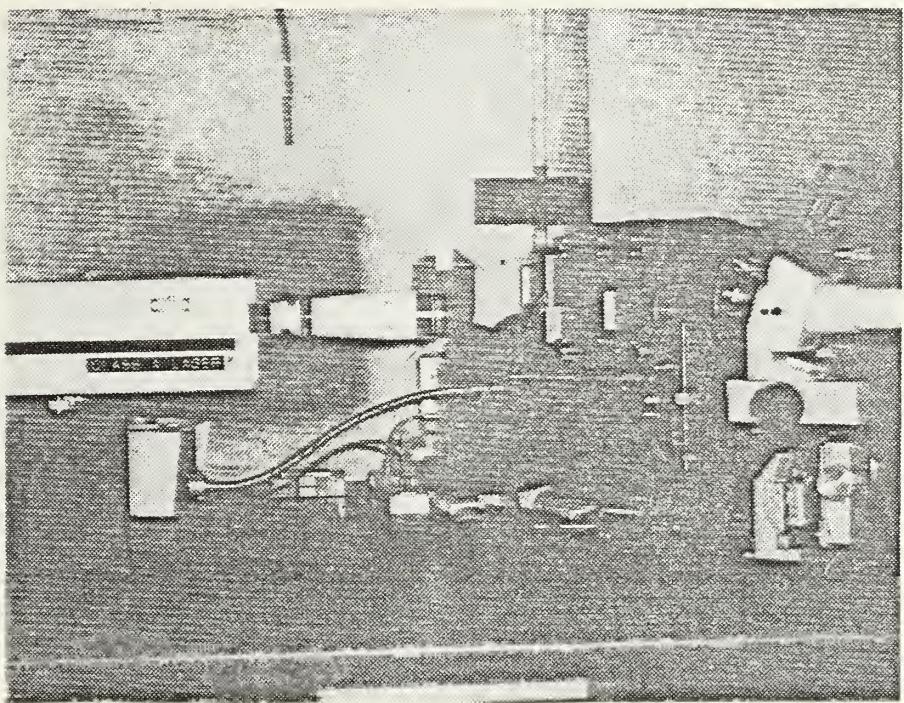


Figure 2.3. Holographic Reconstruction Apparatus

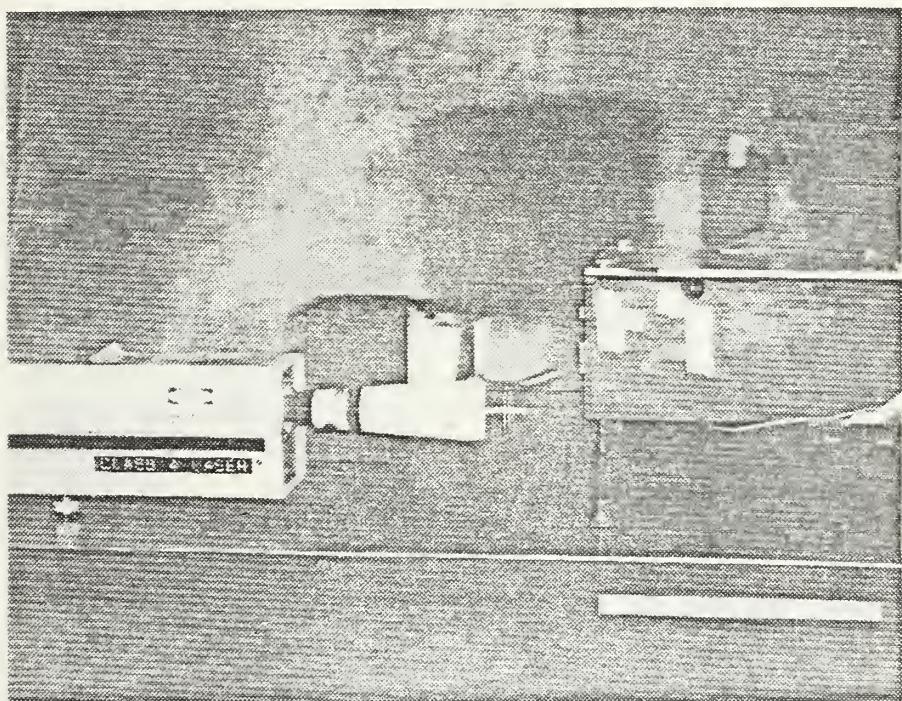


Figure 2.4. Krypton Laser and Holocamera System

3. Three-Dimensional Motor

A short, stainless steel, windowed, 3-D motor with graphite exhaust nozzles, Figure 2.5, was used. This was the same motor as was used by Yoon [Ref. 5]. Figure 2.6 shows the vertically mounted motor as prepared for firing.

The window on the entry side of the motor was enlarged to match the 0.3 inch diameter window on the exit side. This modification allowed more laser light to pass, and provided a greater field-of-view. This was also done in an effort to reduce the defraction of the laser beam around the inlet edges of the smaller window.

The propellant grain was cylindrically perforated and also allowed (in some tests) to burn on the aft end.

4. Propellants

The propellant used for most tests was provided by United Technologies, Chemical Systems Division and had the following composition:

- 83.75% AP
- 14% HTPB
- 2% Al (20 micron)
- .25% Fe_2O_3

Several tests were also made using a propellant provided by the Air Force Rocket Propulsion Laboratory. This propellant had a higher loading and had the following composition:

- 73.59% AP
- 14.82% GAP
- 2.01% Al (40 micron)
- 8.57% TEGTN
- 1.01% HDI

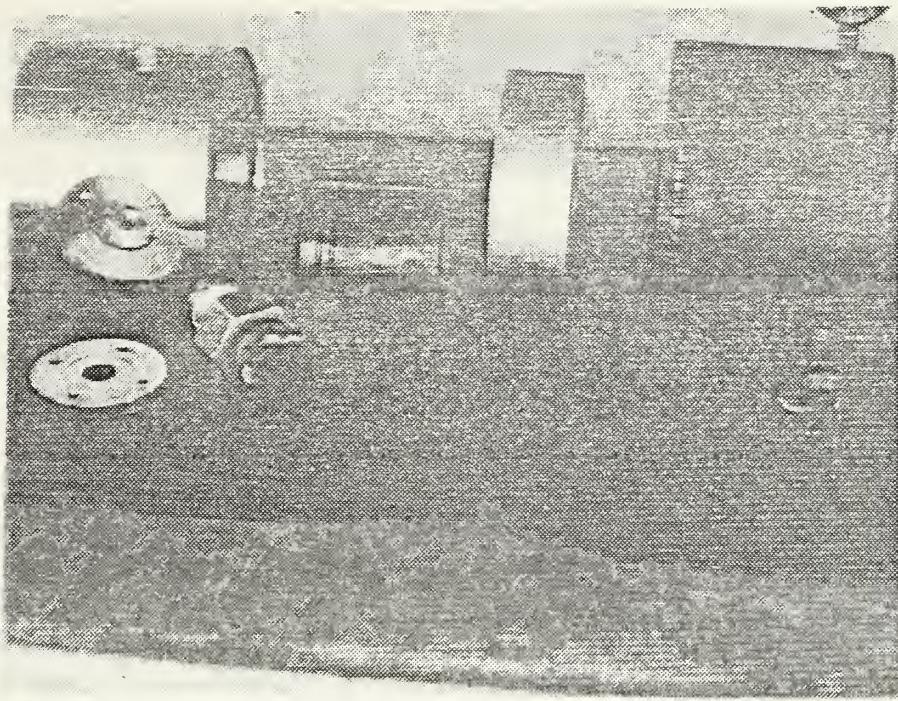


Figure 2.5. 3-D Rocket Motor Components

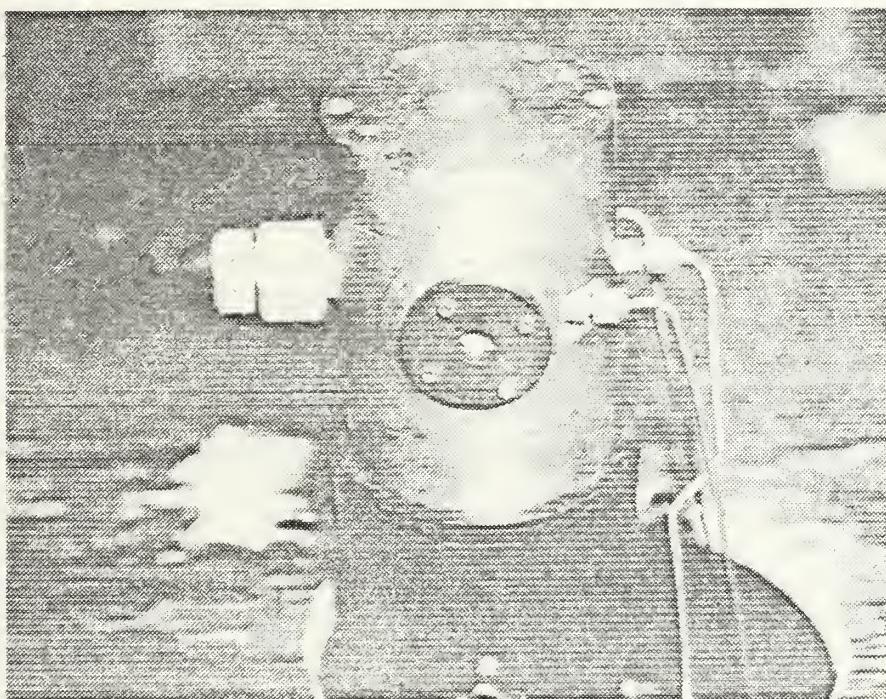


Figure 2.6. Vertically Mounted 3-D Motor

III. EXPERIMENTAL PROCEDURES

A. SYSTEM CALIBRATION

Two methods were used to determine the resolution limits of the holographic system, one utilizing the krypton laser and one utilizing the pulsed ruby laser. The krypton system provided an "ultimate" resolution because of increased system coherence and due to the wavelength match of the hologram as taken and as reconstructed. The pulsed laser system was then used to determine the achievable resolution on the main system. Two targets were used, a Laser Electro-Optics Ltd calibration standard reticle (RR-50-3.0-0.08-102) and a 1951 USAF resolution bar target. In addition, a series of holograms was taken using the pulsed ruby system with the targets set inside the rocket motor.

These calibration holograms showed a resolution of approximately 10 microns with diffuse illumination and less than 5 microns with collimated illumination. The best resolution was obtained using the bar target set inside the windowed motor and collimated light. Previous attempts using collimated light on this target resulted in "fringing" in the hologram. However, the small amount of diffusion provided by the motor windows may have reduced this problem. The LEOS reticle yielded slightly less resolution, but the lower limit of this target was reached or comparable results might have

been achieved. Overall, the different systems gave very similar results in their resolution as can be seen in Table I.

A concurrent thesis topic, by Tom Edwards, is investigating the possibility of image enhancement and automatic data retrieval of the information in the holograms. The images are viewed in a similar manner as is used in this investigation, with a LLTV mounted on the microscope for recording the information. The pictures are then processed using an IBM PCAT. The level of the background noise is reduced, but no appreciable gains in resolution are currently possible. It is hoped that this process can increase the resolution of the images by removing speckle in the diffuse holograms and by removing the schlieren effect found in the collimated holograms. The results of this process to date are included in Table I.

B. PRE-FIRING PREPARATION

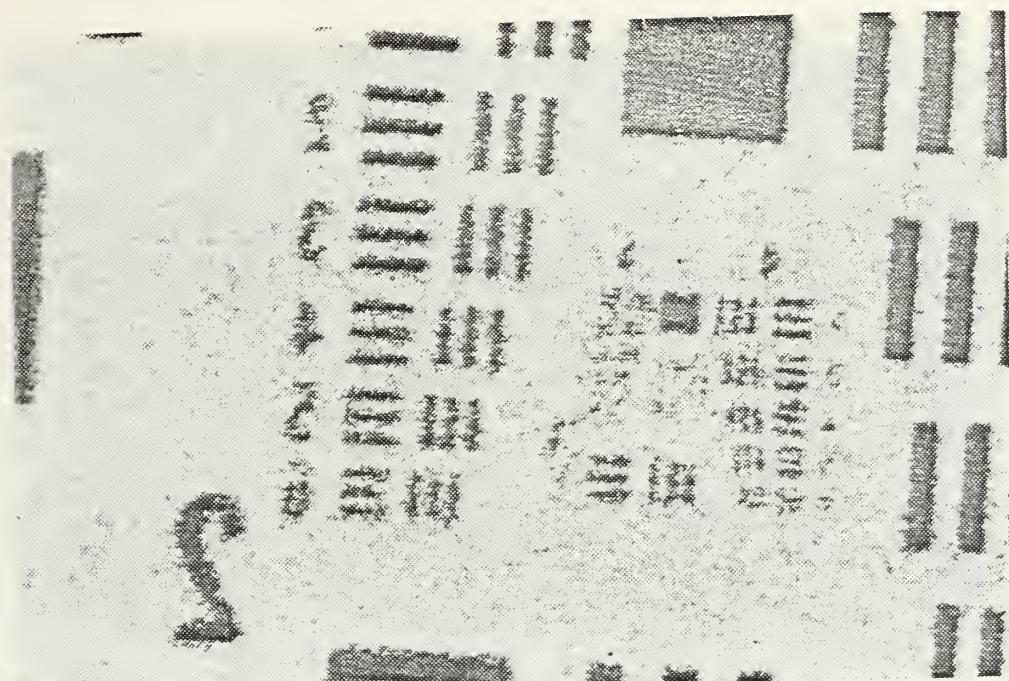
Preparing the system for firing required the following steps to be accomplished:

1. Clean and inspect holocamera optics.
2. Cut, clean, and install propellant in motor casing.
3. Insert windows, nozzle, and end-plates into motor casing.
4. Manufacture igniters by inserting copper wires into igniter bolt, solder ignition wires together, fill with BKNO₃ powder, and seal the open end and wire entry holes with epoxy.
5. Install motor vertically on the test stand.
6. Install and adjust nitrogen purge and pressure lines.

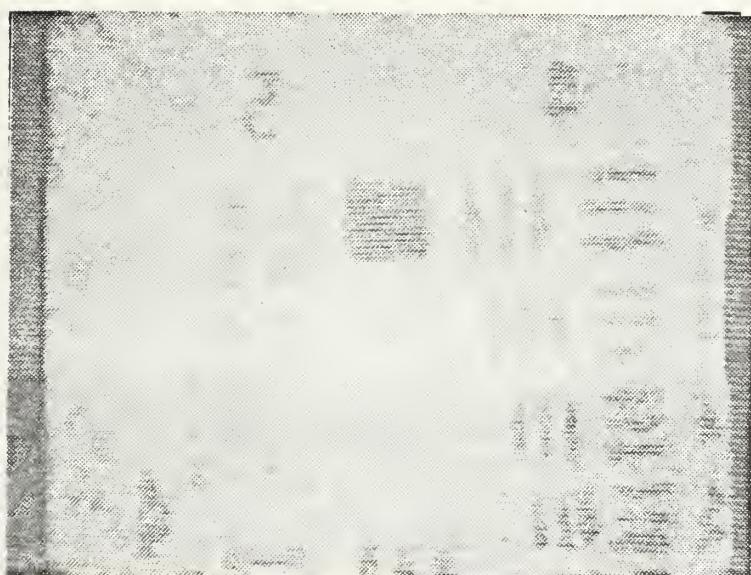
TABLE I

THE RESULTS OF RESOLUTION MEASUREMENTS

ILLUMINATION	TARGET	ILLUMINATION·TYPE	RESOLUTION	FIGURE	ENHANCED FIGURE
Krypton	USAF	Diffuse	8.8 microns	3.1a	3.1b
		Collimated	3.5 microns	3.2a	3.2b
	E-0	Diffuse	11.6 microns	3.3a	3.3b
		Collimated	6.8 microns	3.4a	3.4b
Ruby	USAF	Diffuse	8.8 microns	3.5a	3.5b
		Collimated	8.8 microns	3.6a	3.6b
	E-0	Diffuse	11.6 microns	3.7a	3.7b
		Collimated	8.9 microns	3.8a	3.8b
Windowed Ruby	USAF	Diffuse	9.9 microns	3.9a	3.9b
		Collimated	4.4 microns	3.10a	3.10b

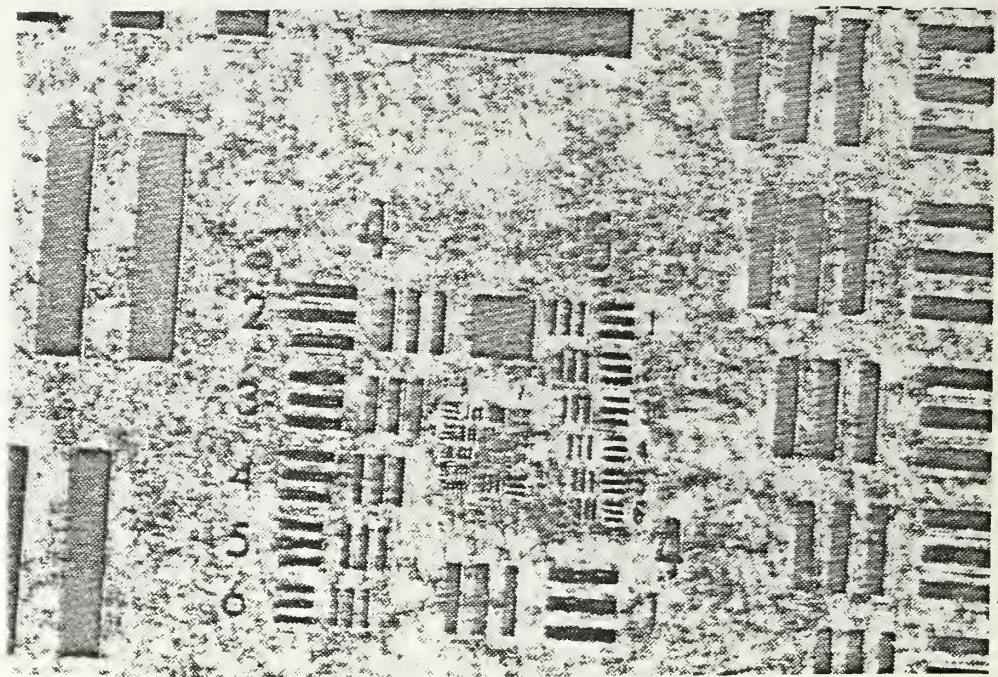


a. Unenhanced Reconstruction

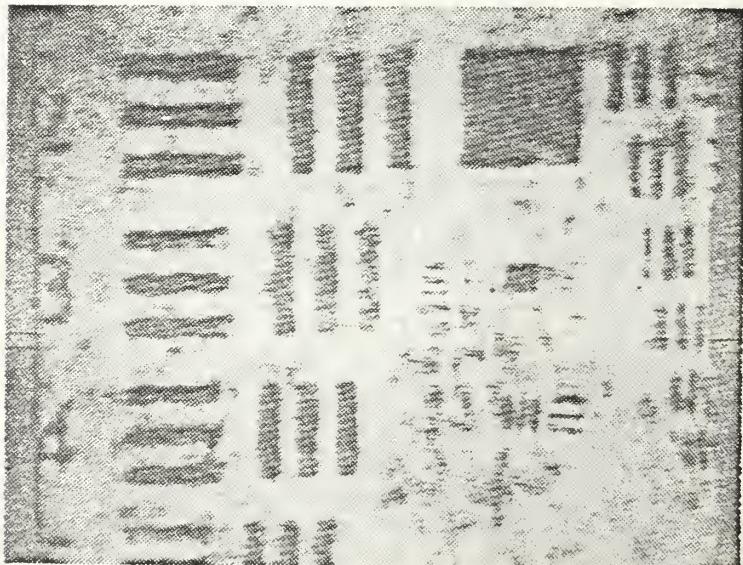


b. Reconstruction With Image Enhancement

Figure 5.1. Photograph of Reconstructed Hologram of USAF Target Using Diffuse Krypton Illumination

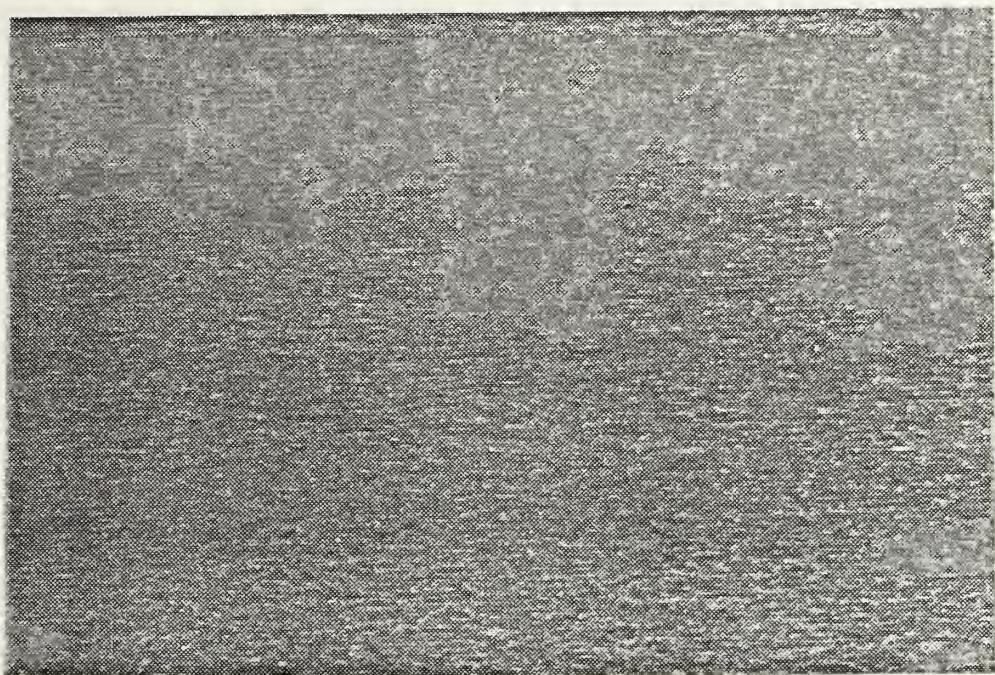


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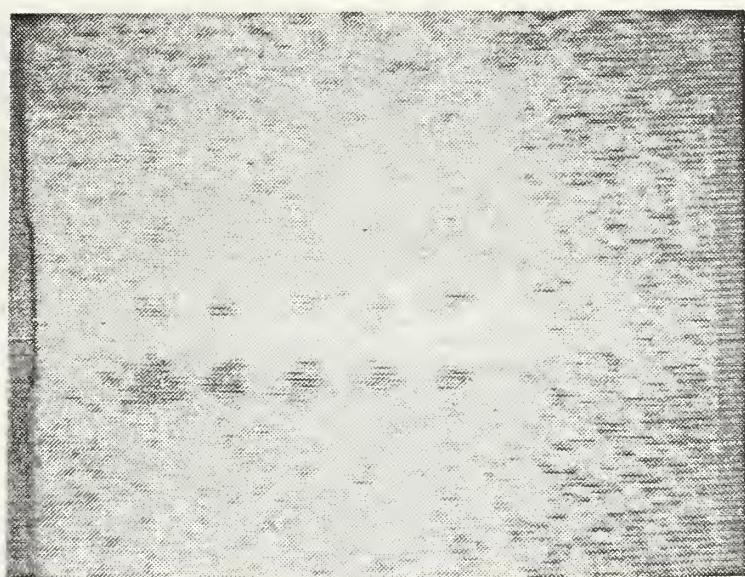


b. Reconstruction With Image Enhancement

Figure 3.2. Photograph of Reconstructed Hologram of USAF Target Using Collimated Krypton Illumination

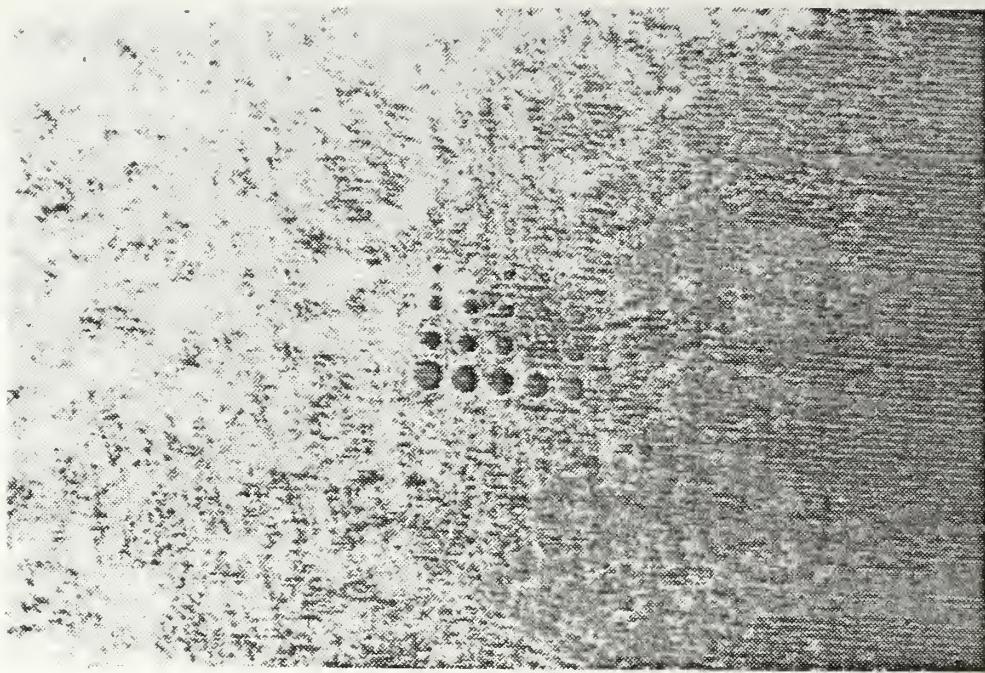


a. Unenhanced Reconstruction

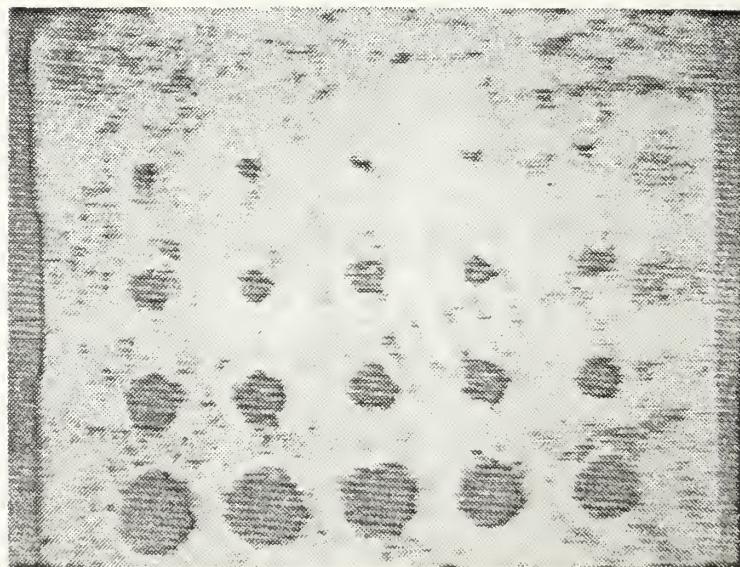


b. Reconstruction With Image Enhancement

Figure 3.3. Photograph of Reconstructed Hologram of LEOS Target Using Diffuse Krypton Illumination

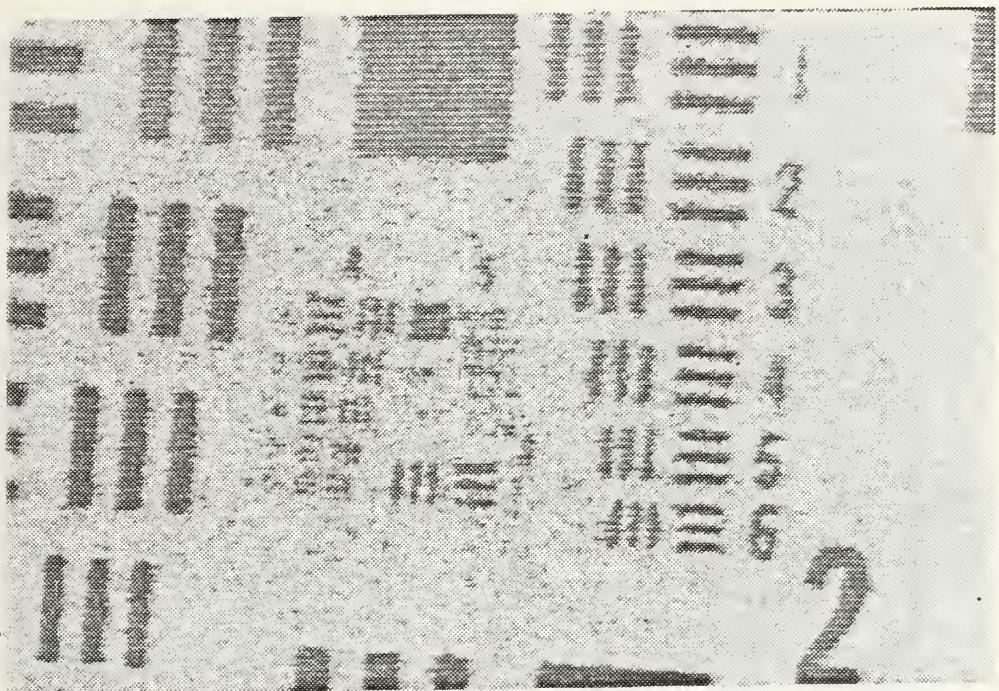


a. Unenhanced Reconstruction

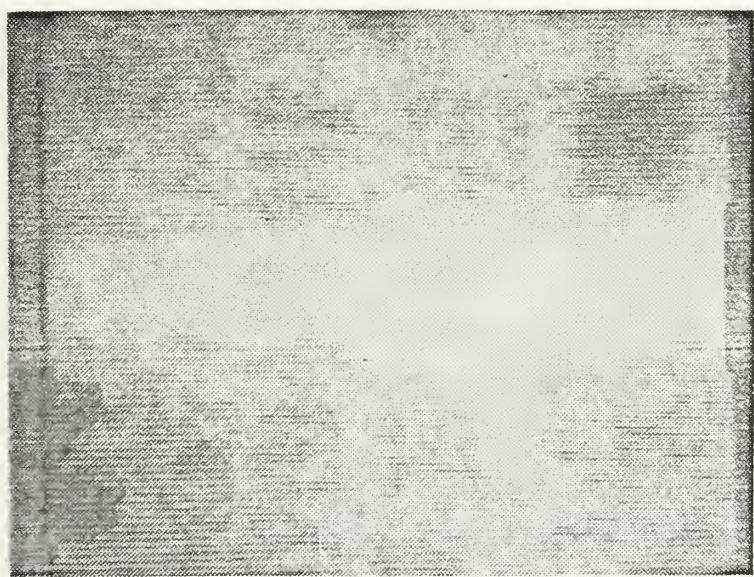


b. Reconstruction With Image Enhancement

Figure 3.4. Photograph of Reconstructed Hologram of LEOS Target Using Collimated Krypton Illumination

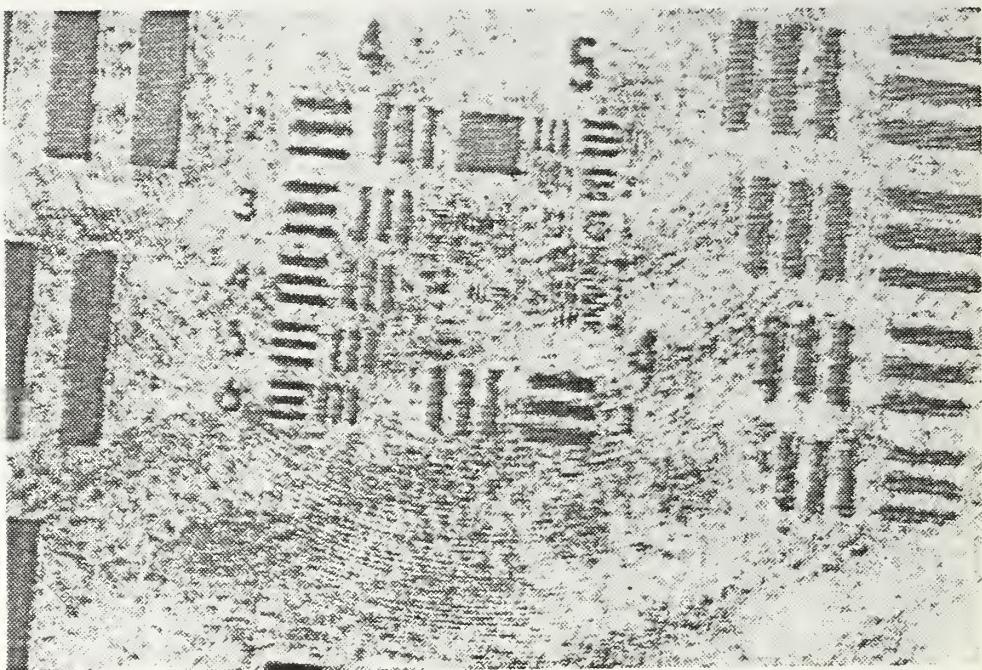


a. Unenhanced Reconstruction

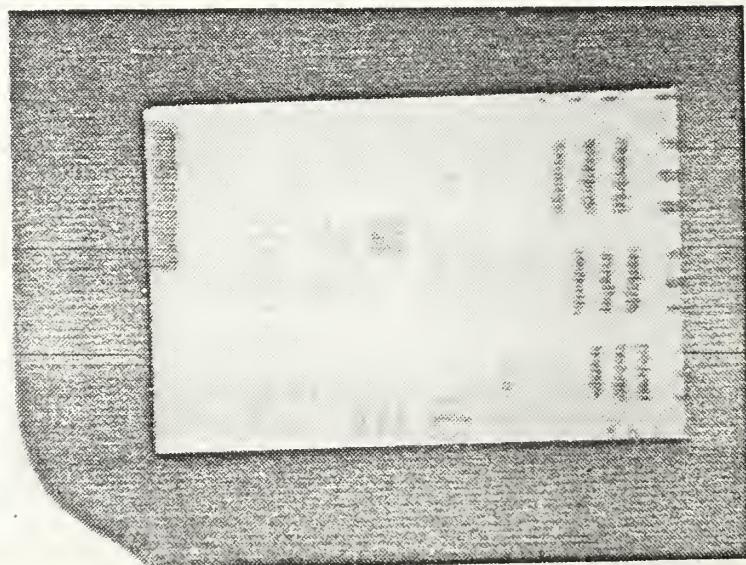


b. Reconstruction With Image Enhancement

Figure 3.5. Photograph of Reconstructed Hologram of USAF Target Using Diffuse Ruby Illumination

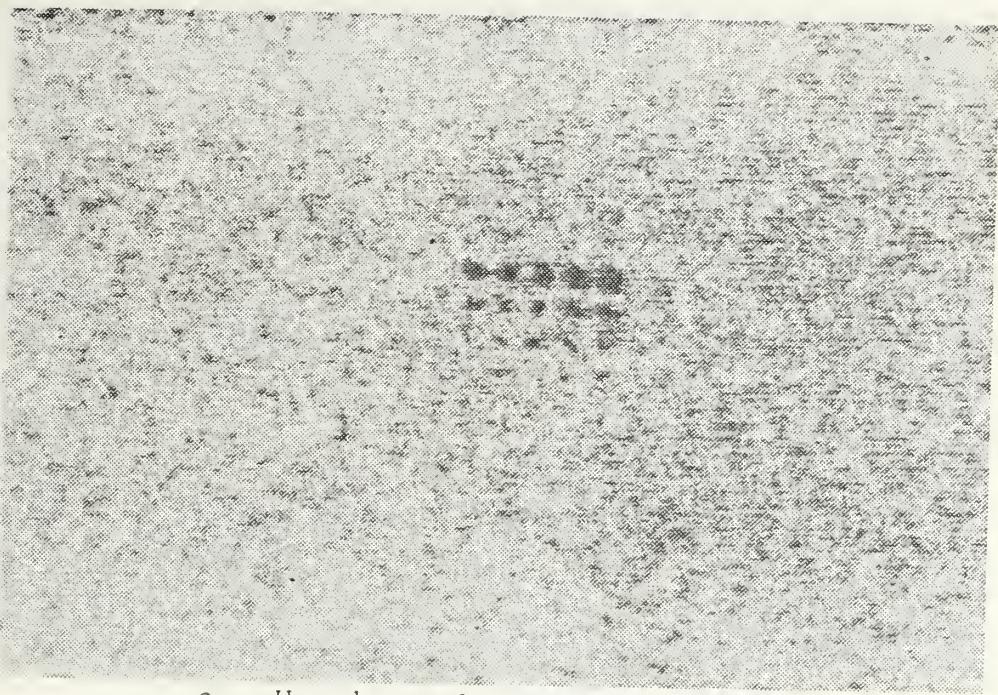


a. Unenhanced Reconstruction

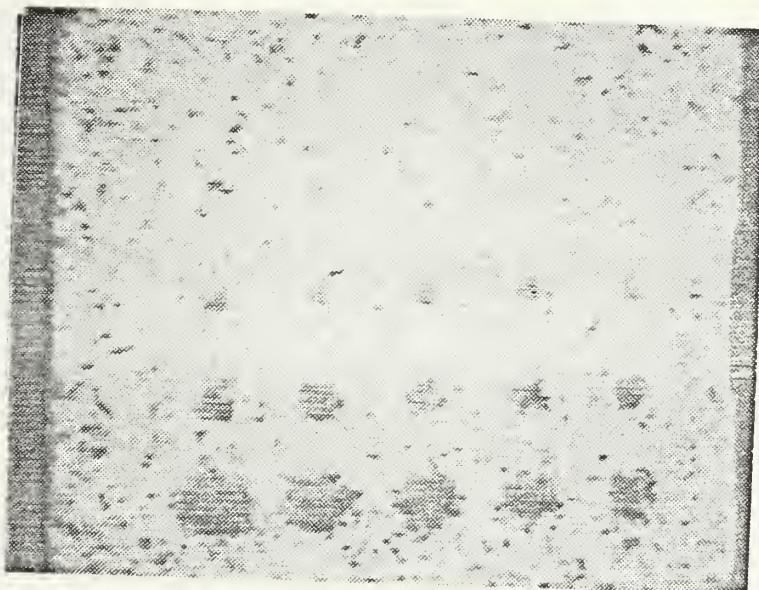


b. Reconstruction With Image Enhancement

Figure 3.6. Photograph of Reconstructed Hologram of USAF Target Using Collimated Ruby Illumination

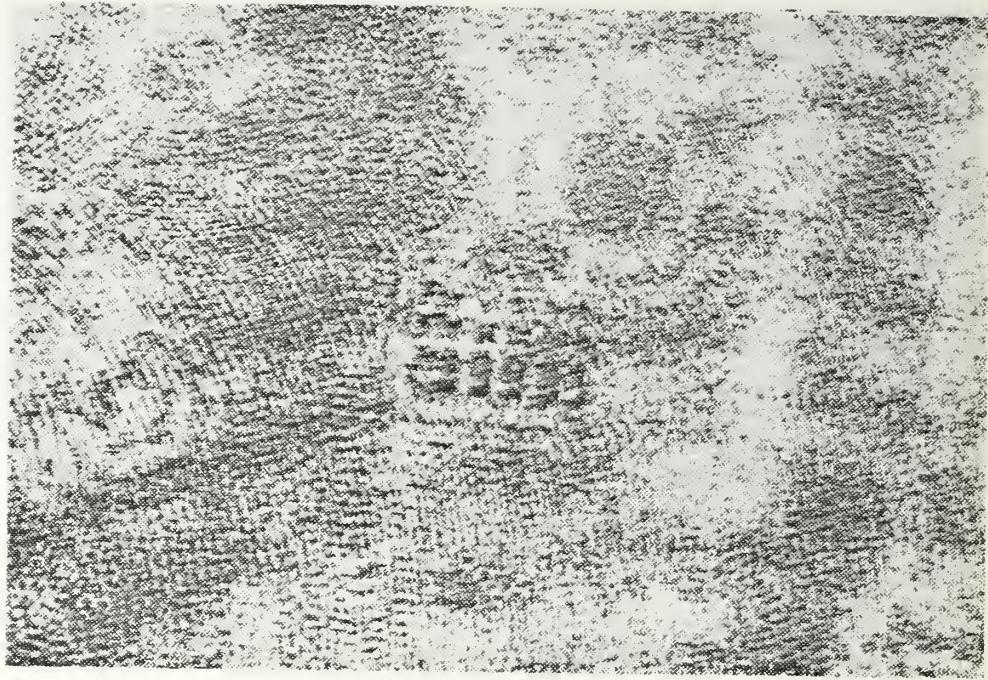


a. Unenhanced Reconstruction



b. Reconstruction With Image Enhancement

Figure 3.7. Photograph of Reconstructed Hologram of LEOS Target Using Diffuse Ruby Illumination

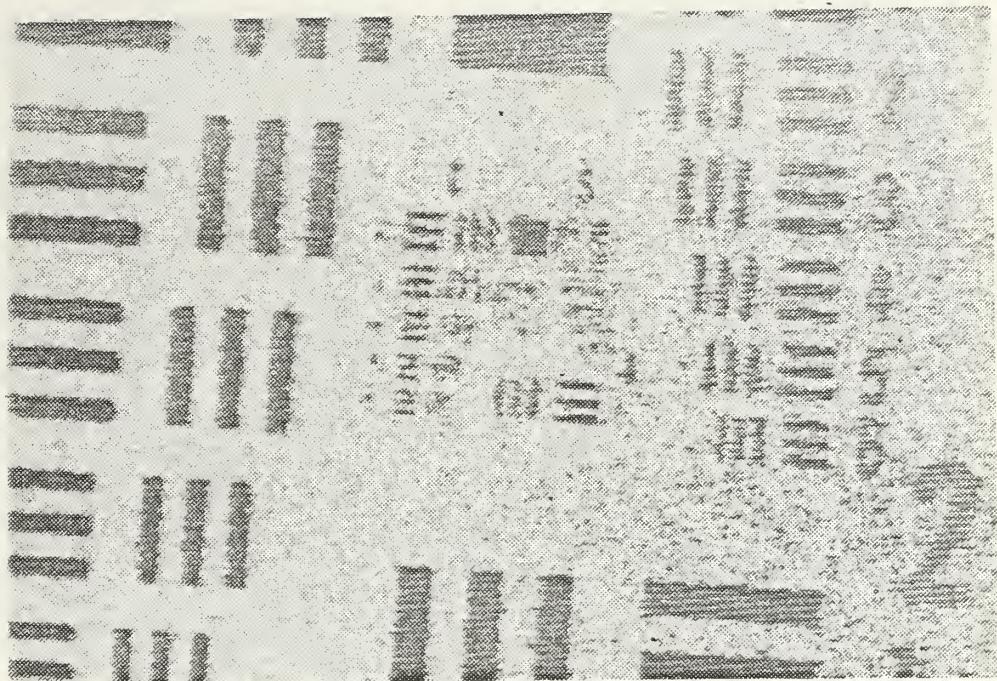


a. Unenhanced Reconstruction

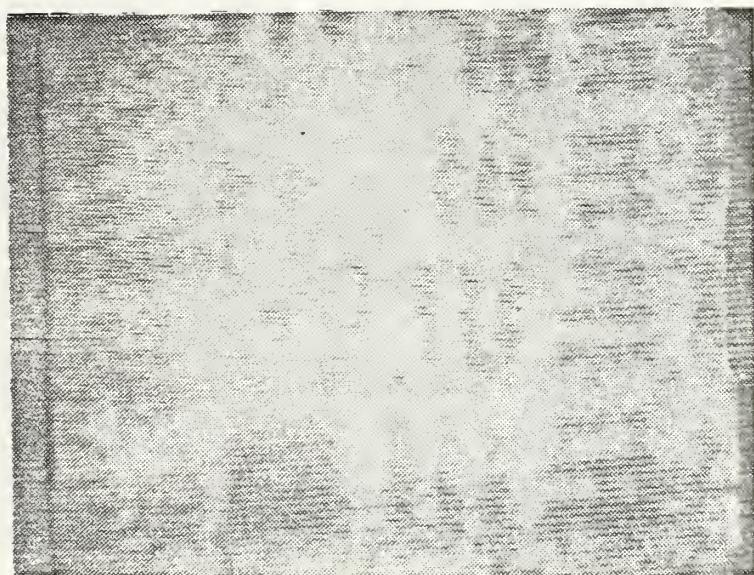


b. Reconstruction With Image Enhancement

Figure 3.8. Photograph of Reconstructed Hologram of LEOS Target Using Collimated Ruby Illumination

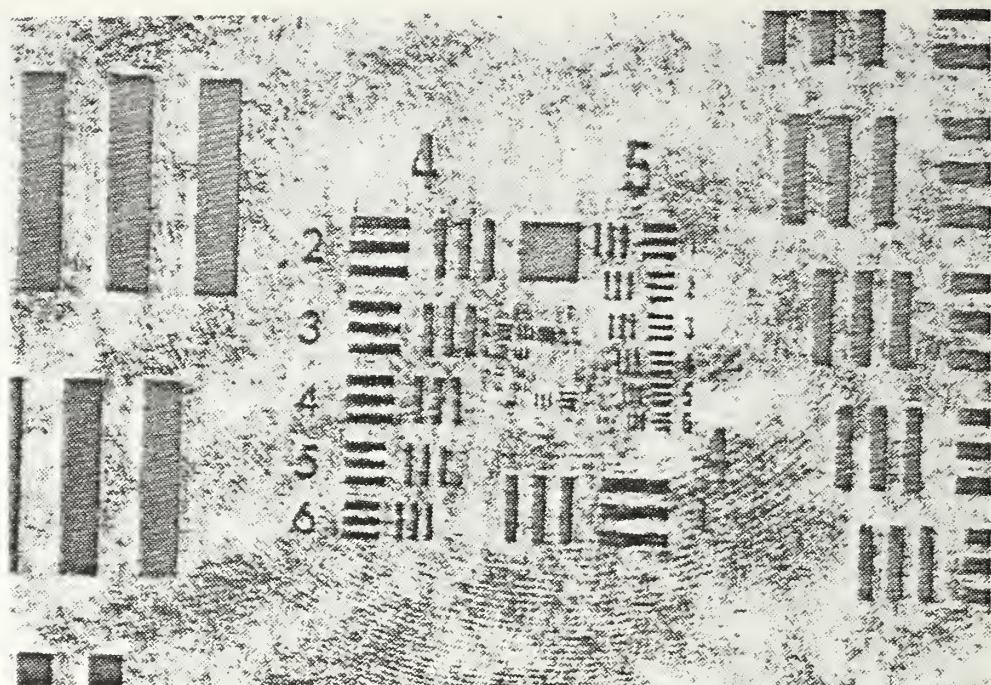


a. Unenhanced Reconstruction

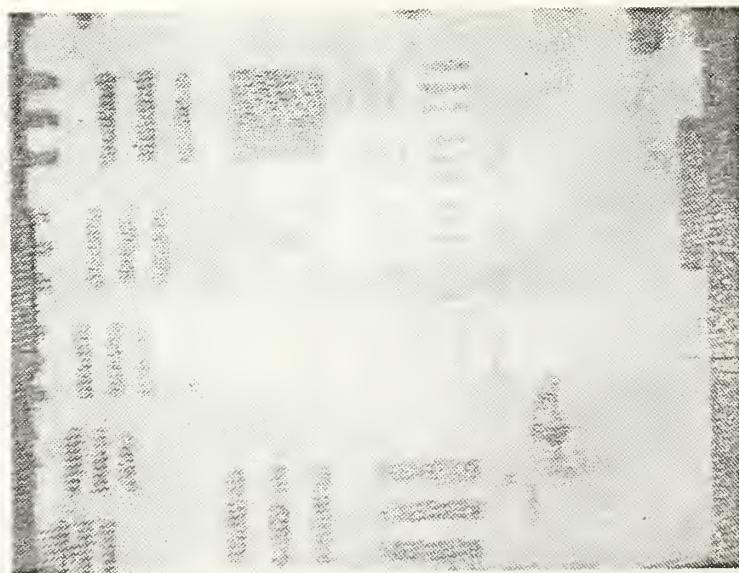


b. Reconstruction With Image Enhancement

Figure 3.9 Photograph of Reconstructed Hologram of USAF Target in 3-D Motor Using Diffuse Ruby Illumination



a. Unehanced Reconstruction



b. Reconstruction With Image Enhancement

Figure 3.10. Photograph of Reconstructed Hologram of USAF Target in 3-D Motor Using Collimated Ruby Illumination

7. Set-up holocamera and check for proper alignment between scene and reference beams.
8. Turn laser on and allow warmup.
9. Load program into HP-9836S and connect all interfaces.
10. Calibrate pressure transducer for program.
11. Ensure remaining power lines and instrumentation are attached.
12. Conduct final continuity/ground check on igniter.

C. MOTOR FIRING SEQUENCE

A Honeywell Visicorder provided a time record of events including a pressure trace, a light diode trace for laser firing, and an events trace. The laser was fired in a computer controlled mode in order to accurately control the hologram timing. This required two motor firings, one to produce a pressure-time trace for each particular propellant and motor geometry and one to take the hologram. A threshold pressure and time delay were then chosen for insertion into the computer program. A typical sequence after completion of the preparation follows:

1. Check all electrical connections.
2. Remove exhaust duct cover plate.
3. Load holographic plate into holocamera.
4. Mount camera box on holocamera and remove reference beam shutter.
5. Check all control panel switches for proper positioning.
6. Insure program readiness.
7. Turn on warning light, secure test area, and sound warning horn.

8. Charge the laser to its firing voltage of 20.75 kV.
9. Turn on nitrogen purge.
10. Start Visicorder.
11. Initiate firing sequence.
12. Upon completion of burn, discharge capacitor bank and secure the laser system and test cell.

D. HOLOGRAM PROCESSING

The holocamera box was removed from the test cell into a darkroom for development by the following method:

1. Immersion in Kodak HRP developer for 15-30 seconds as determined by visual inspection.
2. A rinse in Kodak Stop Bath for 30 seconds.
3. Fresh water rinse.
4. A Kodak Hypo Fix bath was used to set the image, immersion time was 5 minutes.
5. Fresh water rinse for 10 minutes.
6. Kodak Photo-flo immersion for 30 seconds.
7. 2-3 hour air drying.

E. HOLOGRAM RECONSTRUCTION

The holograms were reconstructed using the krypton-ion laser system and microscope in the following manner:

1. The laser system was turned on according to instructions in the operating manual.
2. The exposed plate was remounted into the holocamera box and the box was mounted onto the microscope stand.
3. The laser and hologram were then aligned to a 60 degree angle and the laser shutter and aperture were opened.

4. Focusing of the microscope on the stationary mylar disk was accomplished. The mylar disk was then rotated to blur the speckle and then the holocamera shutter was removed, exposing the image.
5. The image was then viewed with further magnification.

IV. RESULTS AND DISCUSSION OF MOTOR FIRINGS

Transmittance measurements were conducted using the 2% aluminized, AP/HTPB propellant in the three-dimensional motor. Two runs were performed, with each giving different results in the transmittance/pressure correlation. The first run was conducted with the head-end and sides inhibited, a 0.4 inch diameter center perforation and a 0.25 inch diameter exhaust nozzle. A pressure of 540 psi was reached with transmittance greater than zero to about 240 psi. The next run was conducted with the head-end and sides inhibited, a 0.8 inch diameter center perforation and a 0.3 inch diameter exhaust nozzle. A pressure of 270 psi was reached with a transmittance greater than zero until about 150 psi. The inconsistency of the run-to-run results indicate that varying motor geometry may make high pressure holograms possible.

Holograms were attempted using both 2% aluminized propellants. Holograms were obtained at 91, 110, and 280 psi using the HTPB/AP/Al propellant, however, smoke precluded the taking of holograms using the AP/GAP/Al propellant. Table II summarized the conditions for each run.

The particle distribution varied from run to run, with the greatest variation caused by variation of the center perforation diameter of the grain. The small diameter, 0.4 inch, had a dense center core of particles with a lighter distribution

TABLE II
SUMMARY OF TEST CONDITIONS

Propellant Length (inches)	Nozzle Diameter (inches)	Web (inch)	Maximum P_C (psia)	Hologram P_C (psia)	Propellant Type
1.0	.25	1.8	530	280	AP/HTPB/A1
1.0	.25	1.6	500	110	AP/HTPB/A1
1.0	.318	1.8	113	91	AP/HTPB/A1
1.0	.25	1.8	565	--	AP/GAP/A1
1.0	.335	1.8	290	--	AP/GAP/A1

Note: all grains inhibited on head-end and sides, #1 and #3 also inhibited on aft-end.

towards the walls. The larger diameter, 0.8 inch, resulted in a more even distribution throughout the motor volume. No pressure/particle size correlation could be established. Table III contains the hologram information. The effects of present image enhancements can be seen in Figure 4.4. This concurrent thesis holds the promise of much faster data retrieval from the holograms, which is an extremely tedious task under present conditions. In addition, this process eliminates much of the background noise from the holograms. This process will allow the choice of diffuse or collimated holograms, whichever best fits the situation. The use of collimated light may make penetration of the dense combustion products possible at higher pressures.

TABLE III
THE RESULTS OF MOTOR FIRINGS

Propellant Type	Reference Filter Transmittance (%)	Beam N.D.	Hologram pc(psia)	Figure Number	Remarks
AP/HTPB/A1	30		280	4.1	
AP/HTPB/A1	13		110	4.2	
AP/HTPB/A1	30		91	4.3	
AP/GAP/A1	30		560	---	Hologram not recorded
AP/GAP/A1	30		240	---	Hologram not recorded

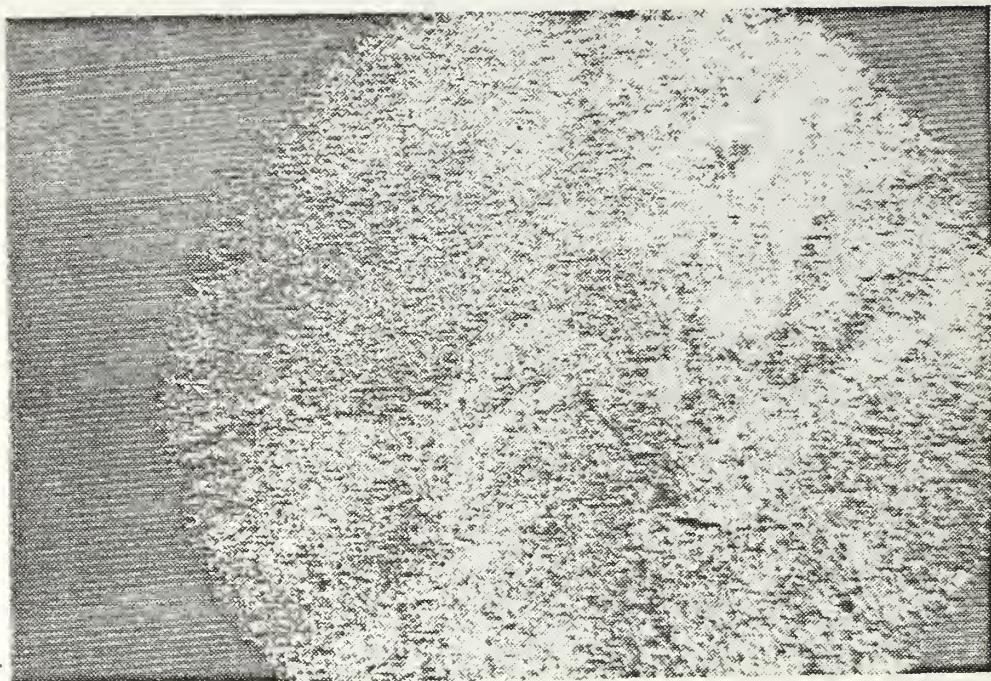


Figure 4.1. Photograph of Reconstructed Hologram of Propellant Burned at 280 psi

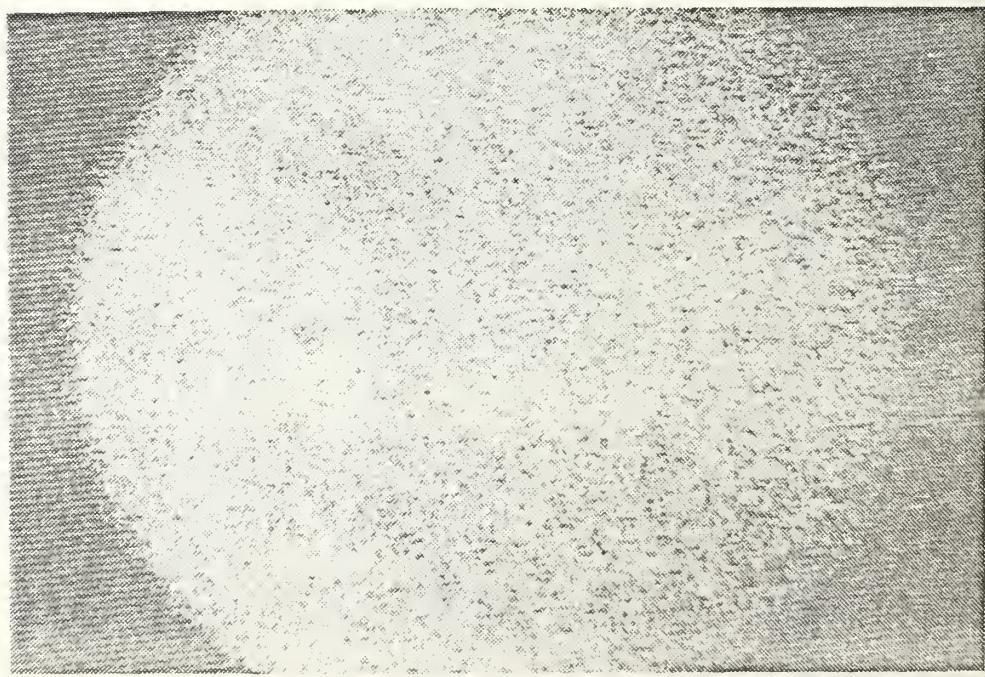


Figure 4.2. Photograph of Reconstructed Hologram of Propellant Burned at 110 psi

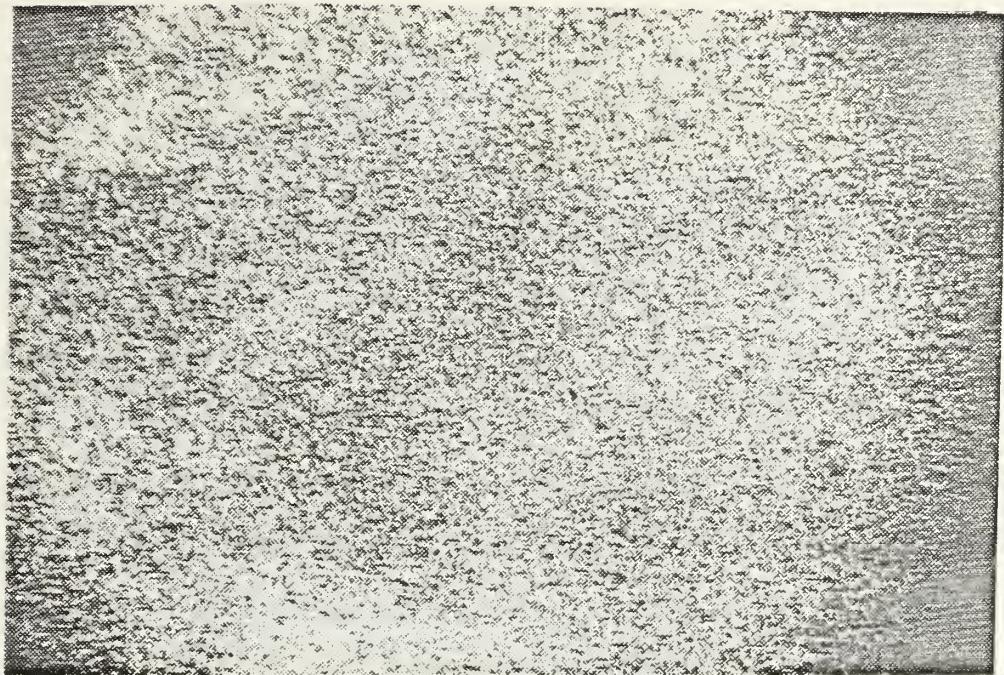


Figure 4.3. Photograph of Reconstructed Hologram of Propellant Burned at 91 psi

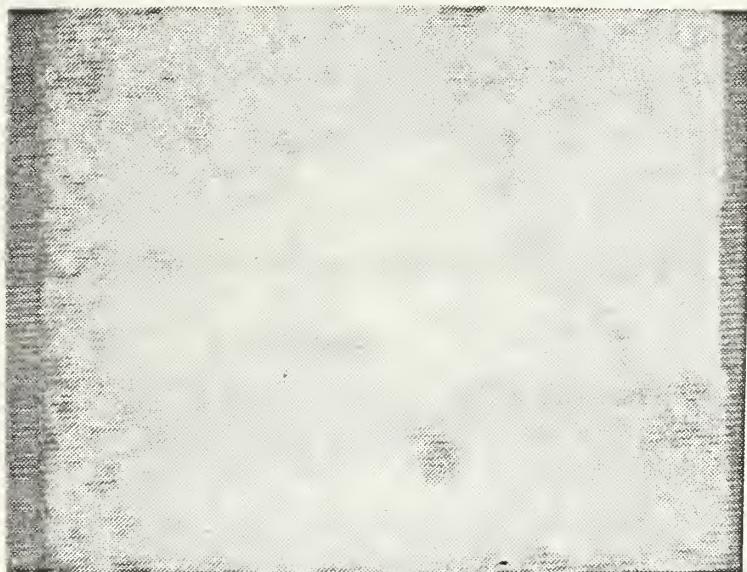


Figure 4.4. Photograph of Reconstructed and Enhanced Hologram of Propellant Burned at 91 psi

V. CONCLUSIONS AND RECOMMENDATIONS

Good quality holograms were obtained in a small 3-D motor using 2% aluminized, composite propellants to pressures of 280 psia.

Two major difficulties were encountered during this investigation, the inability to exactly time the taking of the hologram and the location of the motor windows with respect to the propellant grain. The ability to time the hologram exactly can eliminate many problems currently being encountered, such as run-to-run inconsistencies in the pressure/time trace and smoke production. In the current motor, the windows are located at the end of the propellant grain, limiting the propellant to a 1 inch grain length, and reducing the spread of the particles and smoke throughout the motor volume. Variations in motor grain geometry and the addition of a motor extension on top of the current motor would allow a longer distance for the particle distribution and smoke to spread and thus allow higher pressures to be attempted. Some modifications to the current computer program which controls the firing of the laser could also eliminate the timing problems.

The introduction of a different type of laser, such as YAG, would allow an opportunity to see if varying the laser wavelength might reduce the effects of smoke on transmittance.

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